Tests and Interpretation of Small Fatigue Crack Growth in Metallic Rotorcraft Structures with Emphasis on the Statistical Characteristics

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Participants

Faculty

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Outline

- **Motivation / Background / Objectives**
- **Small Fatigue Crack Growth Data**
  - From micro-notches
  - From smooth surfaces ("cluster cracks")
- **Statistical Aspects**
  - Confidence Intervals
  - Scatter
  - Extrapolation

Background

- Small cracks: Of the order of 1-10 grains
- Considerable part of total fatigue life is spent in the "small crack growth" regime
- Need of an acceptable method to include in fatigue life codes
- Appropriate statistical representation

Background, Cont.

- **The role of the local microstructure in the initial stages of fatigue crack growth has been discussed by**
  - **Miller (1982)**
  - **Chan and Lankford (1984)**
  - **Leis et al (1986)**
  - **Navarro and De Los Rios (1988)**
  - **Tanaka and Akiniwa (1989)**

Background, Cont.

- **Features of small crack growth**
  - **Growth-arrest**
  - **Coalescence of microcracks**
  - **Growth at smaller SIFs and at faster rates than equivalent long cracks**
  - **Scatter significantly greater than that for long cracks**

Background, Cont.

- Smooth Surfaces: micro-multi-site cracking
  - Crack initiation consists of localized clusters of micro-cracks
  - Lab tests on polished specimens
- Flaws, Micro-Notches, Nicks
  - Cracks can also emanate from flaws such as nicks
  - H-53 helicopter failure report (Crawford, 1990): fastener holes, internal corners with small radii and sections with abrupt changes in thickness

Background, Cont.

- *Kardomateas, Carlson, Soediono(1993)*
  - Study on applicability of K- singularity for small a/ρ
- *Carlson and Halliday (1998)*
  - Tests on smooth bar 2024-T351 (thumbnail cracks) and with a corner crack
- *Newman (1992)*
  - Effective stress intensity factor range, closure effects

Background, Cont.

- *Cox and Morris (1988)*
  - random, 2D pattern of grains and Monte Carlo simulation of small cracks growing under Mode I
- *Steadman, Carlson and Kardomateas (1998)*
  - <u>“Graftals”</u> (used to describe growth in biological systems) combined with “trapping” and “untrapping” conditions

Background, Cont.

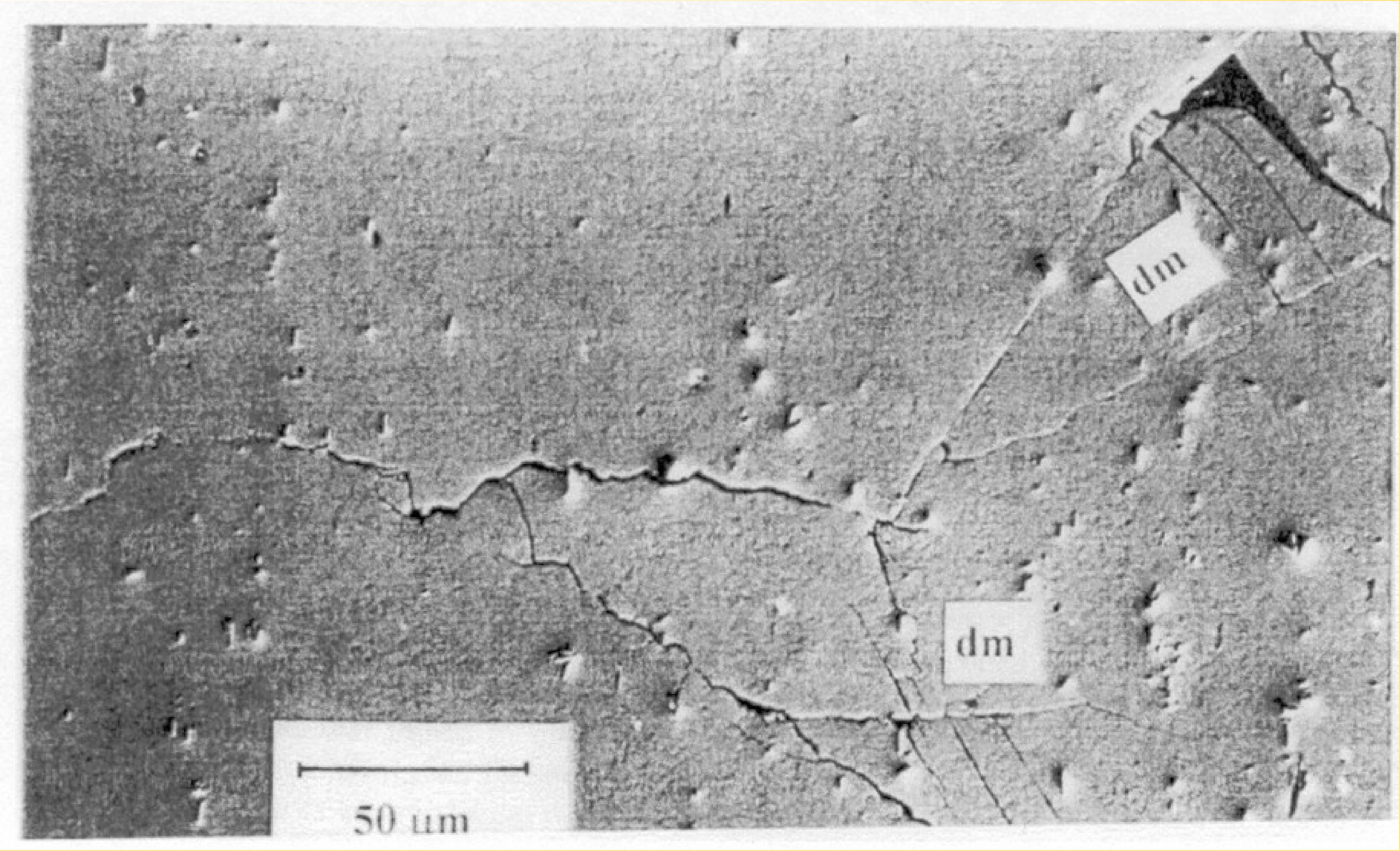
- Schijve (1994): differences between <u>lab</u> and <u>service</u>

- Stolarz and Kurzydlowski (1998): Smooth bars of Zircaloy-4. <u>Densities</u> of <u>cracks of the order of the grain size</u> much larger up to 50% of fatigue life; beyond that long dominant crack

Background, Cont.

- Limitations of simulation studies
  - Local, effective SIFs based on linear, isotropic elasticity do not account for varying crystallographic orientations
  - 2D analyses do not account for 3D effects
  - Variation of grain shapes depending on processing, e.g. elongated, pancake, etc
  - Complexity of forms of localized damage and branching (Carlson, Steadman and Kardomateas, 2001 on Small Fatigue Crack Morphology)

Morphology of Small Crack Growth

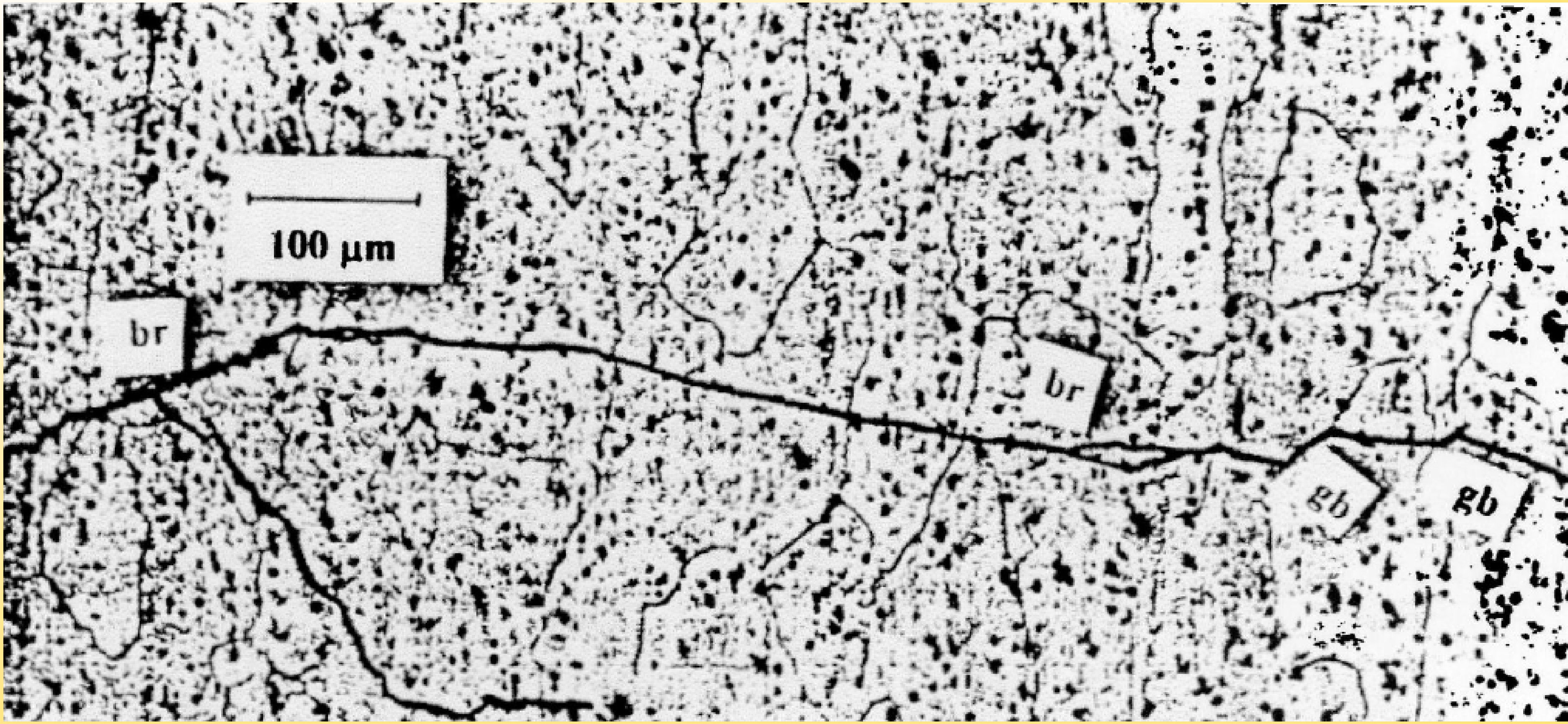


Deviation from planar, crack branching, etc.

Background, Cont.

- **When cracks are of the order of the grain size, the medium through which a crack front moves is <u>neither homogeneous nor isotropic</u>**
- **Details of crack path advance dependent on microstructure**

Polished and Etched Outer Surface

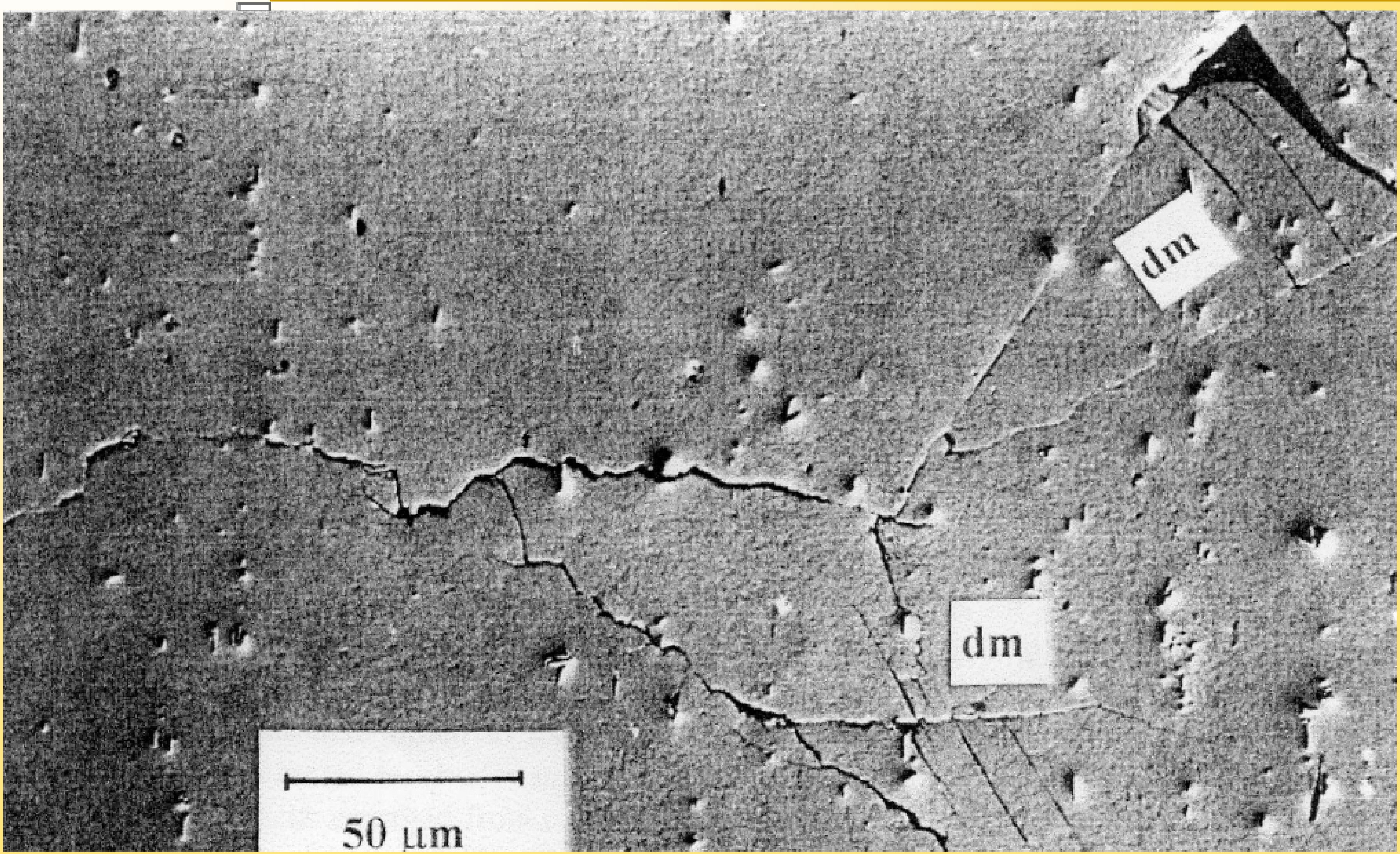


br – branching

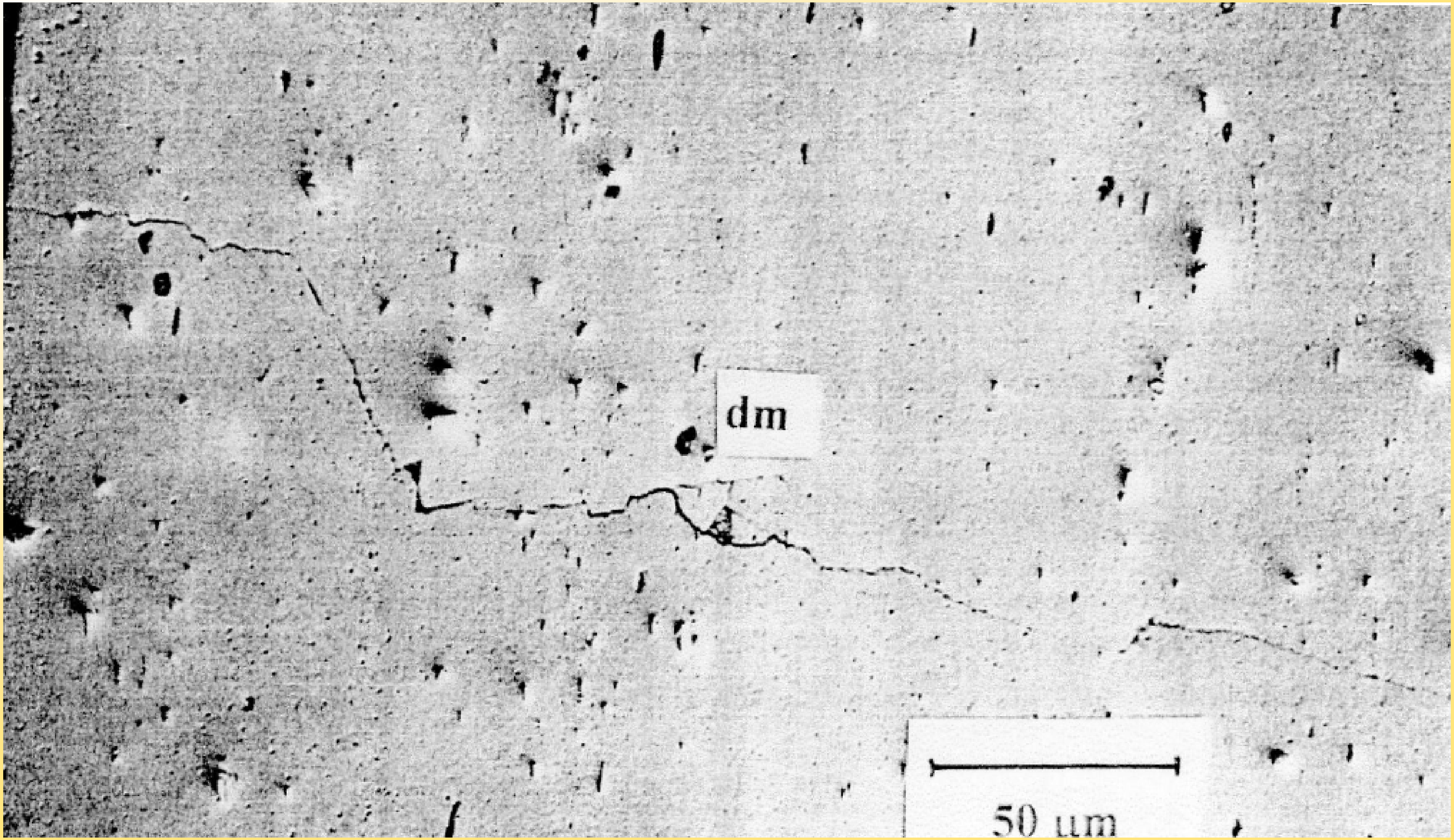
gb – grain boundary deflection

dm – local damage

Polished Surface 250 microns Below Outer Surface



Polished Surface 750 microns Below Outer Surface



Topics

- *Scatter in small fatigue crack growth from micro-notches*

- ***Scatter in small fatigue crack growth from smooth surfaces ("cluster cracks").***
  - *Micro, multi-site cracking.*

Micro-Notches
Completed Research

- ***Test Setup***
  - *Alloy: 6061-T651 (rod form)*
  - *Grain size: Transverse -200 microns*

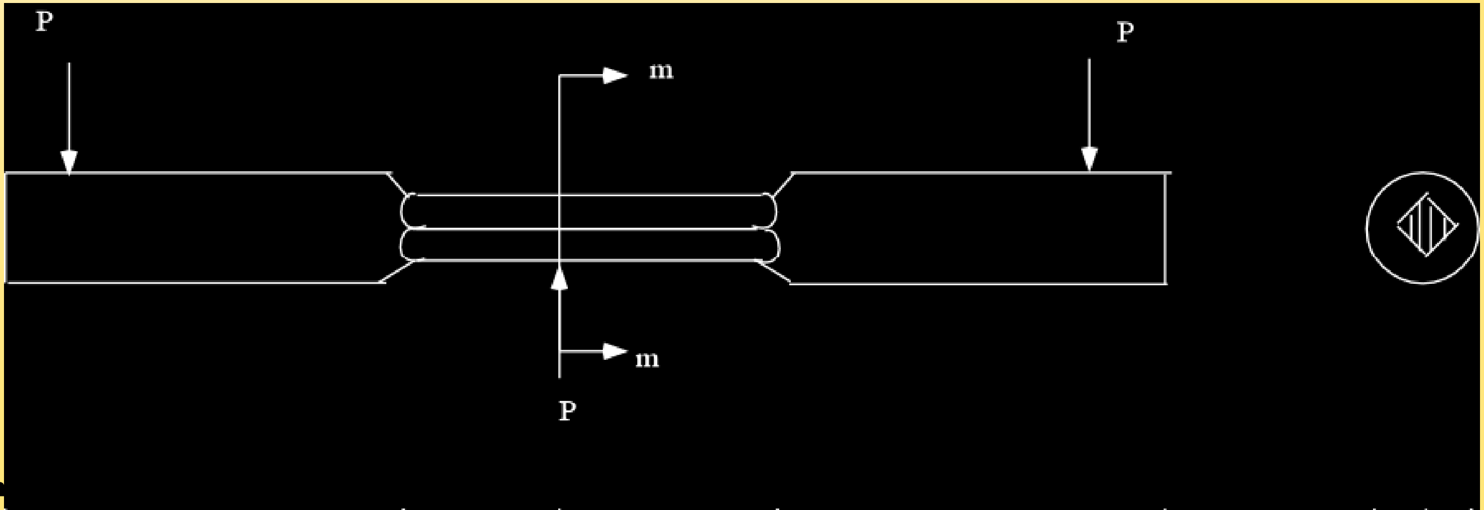
    Longitudinal - 350 microns
  - *Properties: 0.2% offset yield stress – 283 MPA*

    ultimate strength – 293 MPA
  - *Test specimen: Square cross-section*

    150 micron notch corner edge
  - *Loading condition: Bending about a cross section diagonal*

Micro-Notches, Cont.

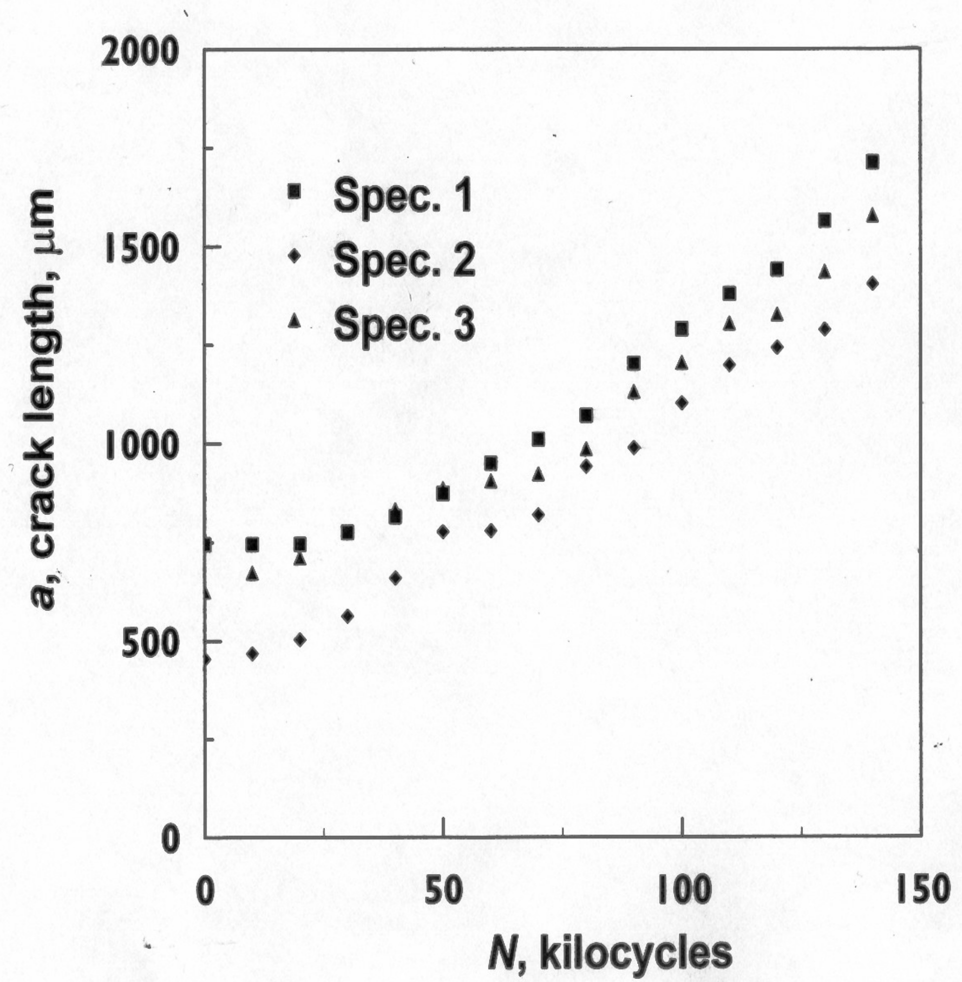
- **Corner crack in 3-pt bending**
  - **Midpoint corner cracks were initiated at a notch with a depth of 150 μm**
  - **sinusoidal loading at 10 Hz with a load ratio of 0.2**
  - **Maximum nominal stress: 0.8 of the yield stress**
  - **Crack monitoring with telemicroscope: sensitivity of readout: 10 μm**



Micro-Notches, Cont.

Test Data/Details

- 150 μm notch
- Readings every 10,000 cycles
- 65,000 cycles "fatigue precracking" (to go beyond notch effects)



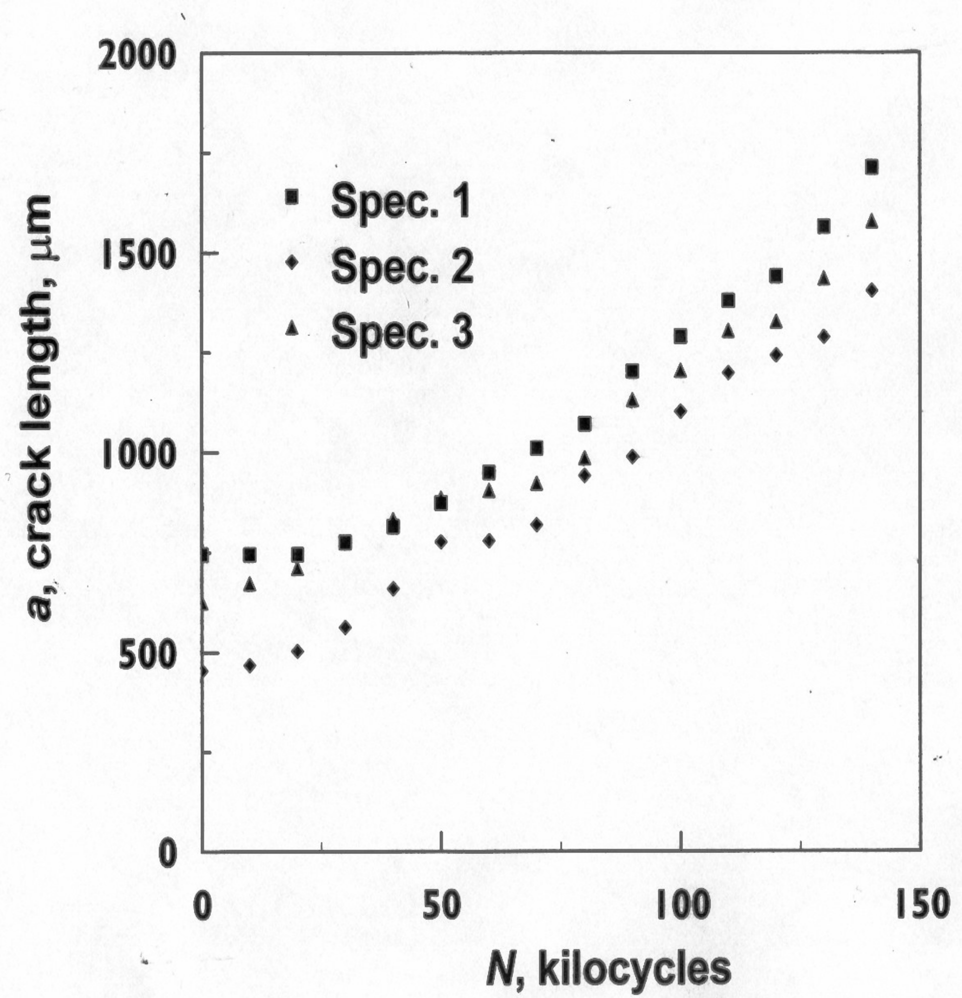
Micro-Notches, Cont.

Growth Rates

– Beyond 1,000 μm, rates begin to converge

– At this length, crack front is intersecting about 10 grains

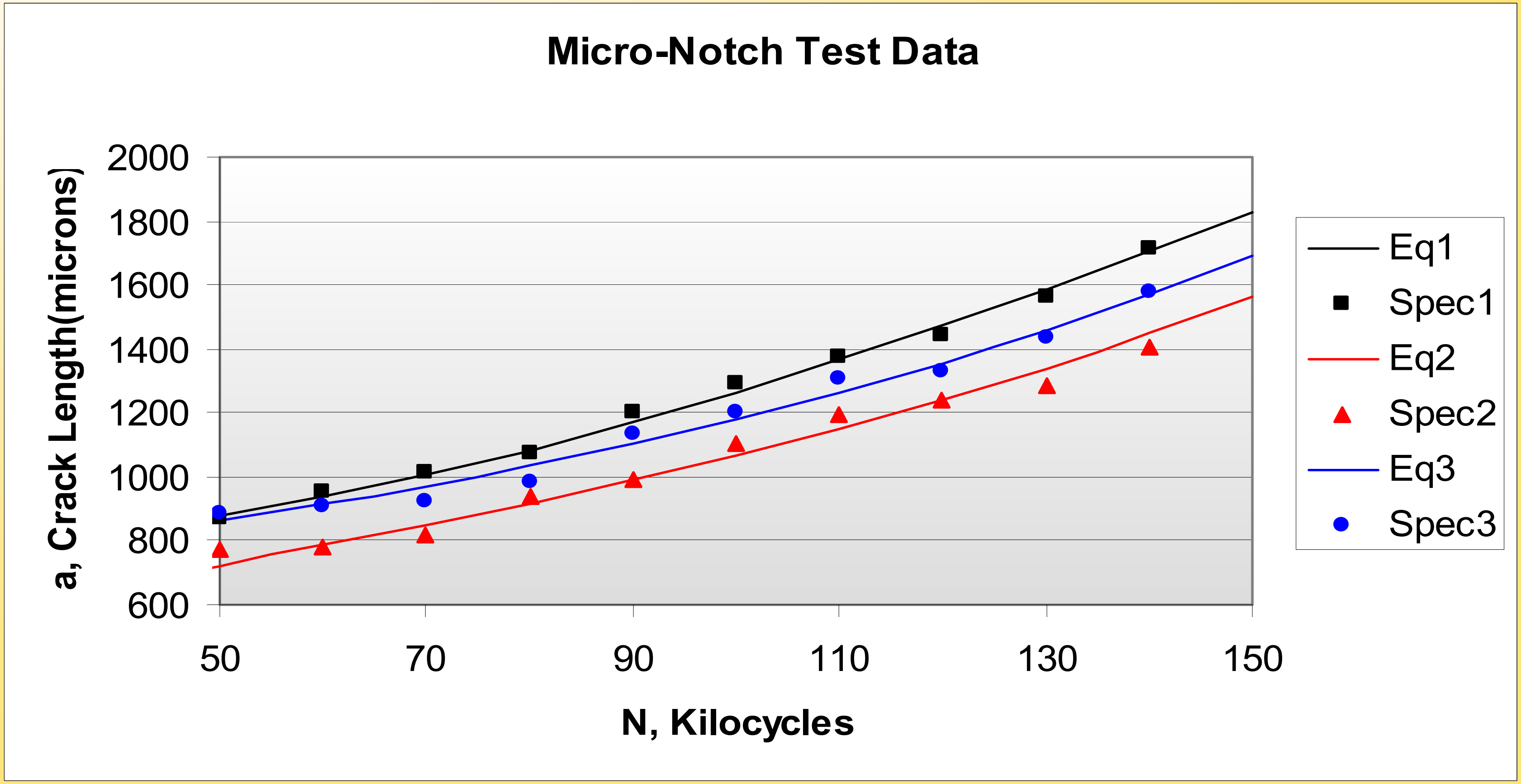
– Beyond 1,500 μm, “long” crack growth



Test Data from Micro-Notches

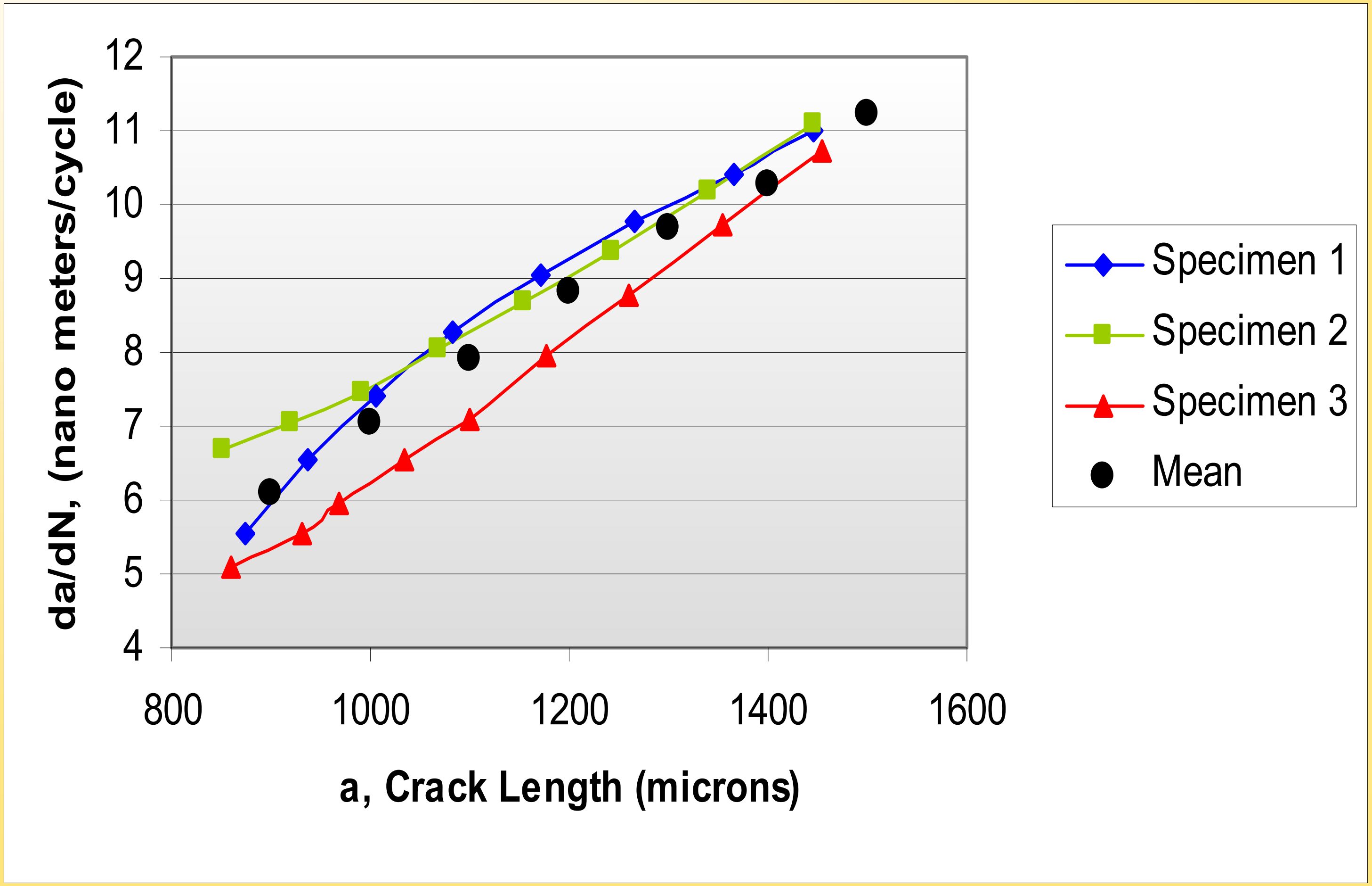
- ***Cubic Regression Analysis Performed on Data***

$$a = C_1 + C_2 N + C_3 N^2 + C_4 N^3$$



Regression Analysis

- *da/dN computed by differentiating resulting equations*



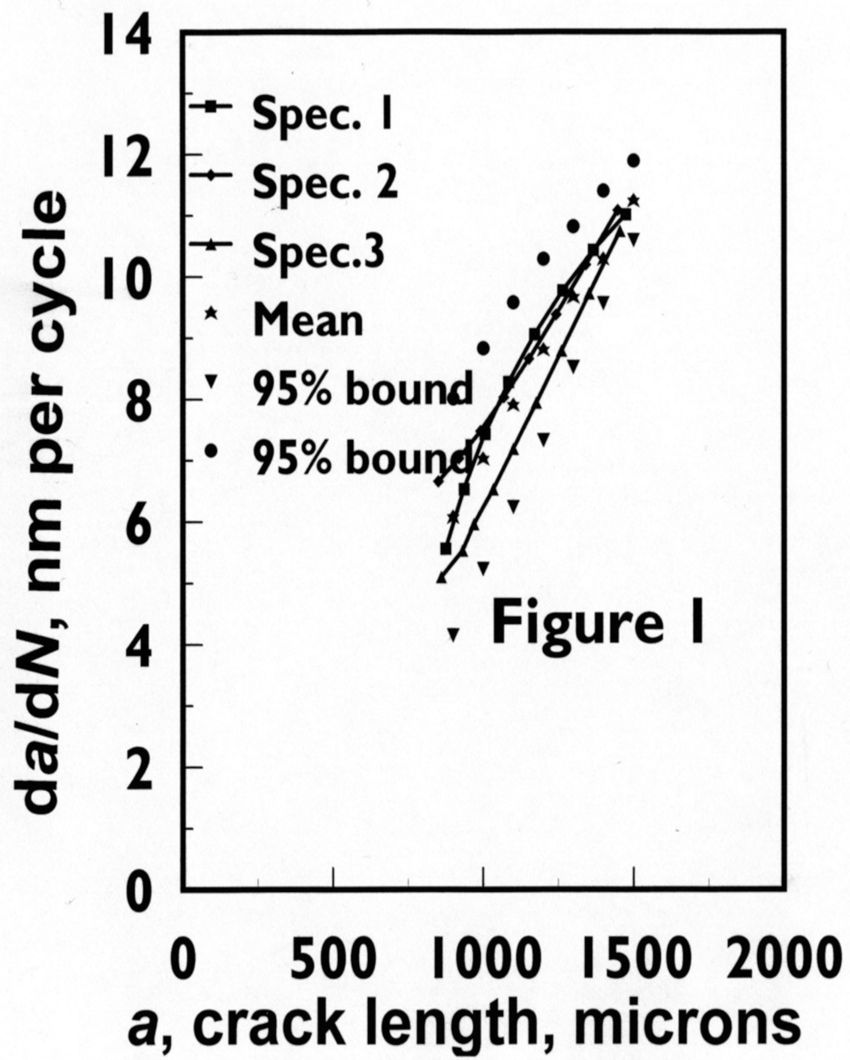
Micro-Notches, Cont.

da/dN vs a with 95% bounds

- Student's t analysis of growth rates for 95% confidence intervals

- Cartesian

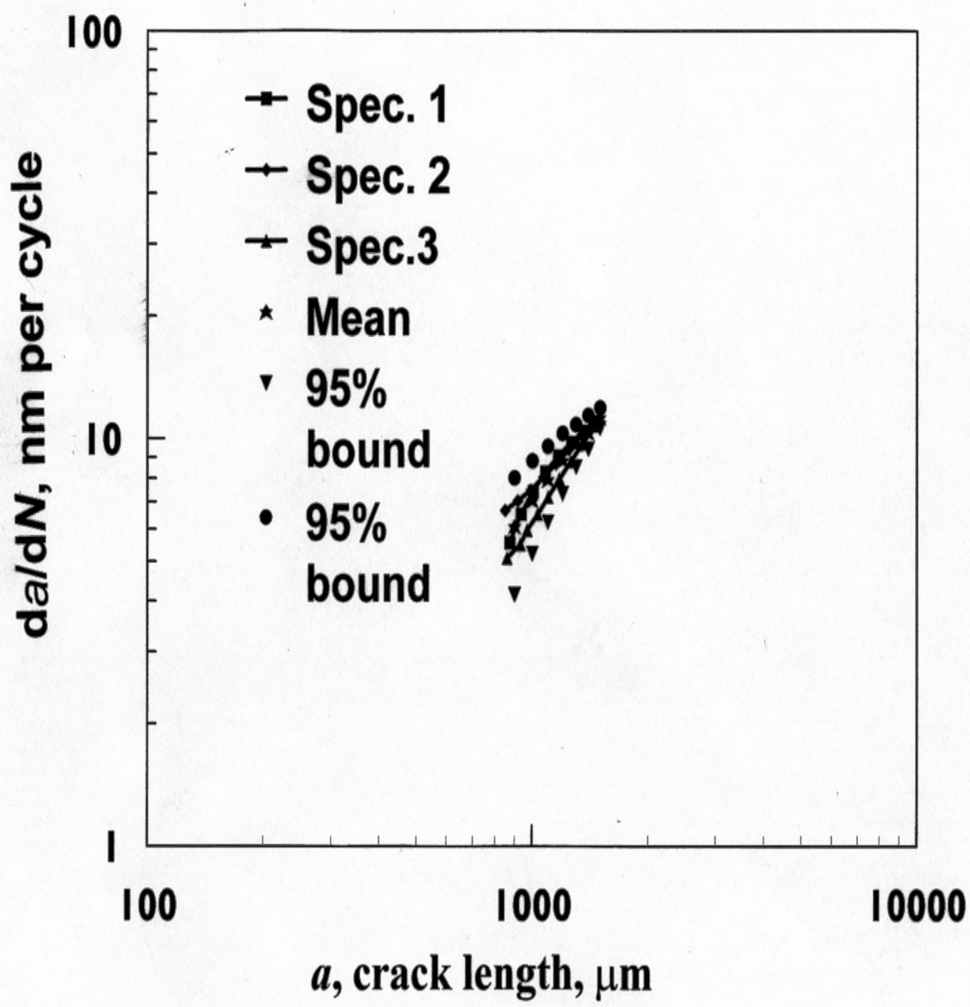
- Rates eventually merge



Micro-Notches, Cont.

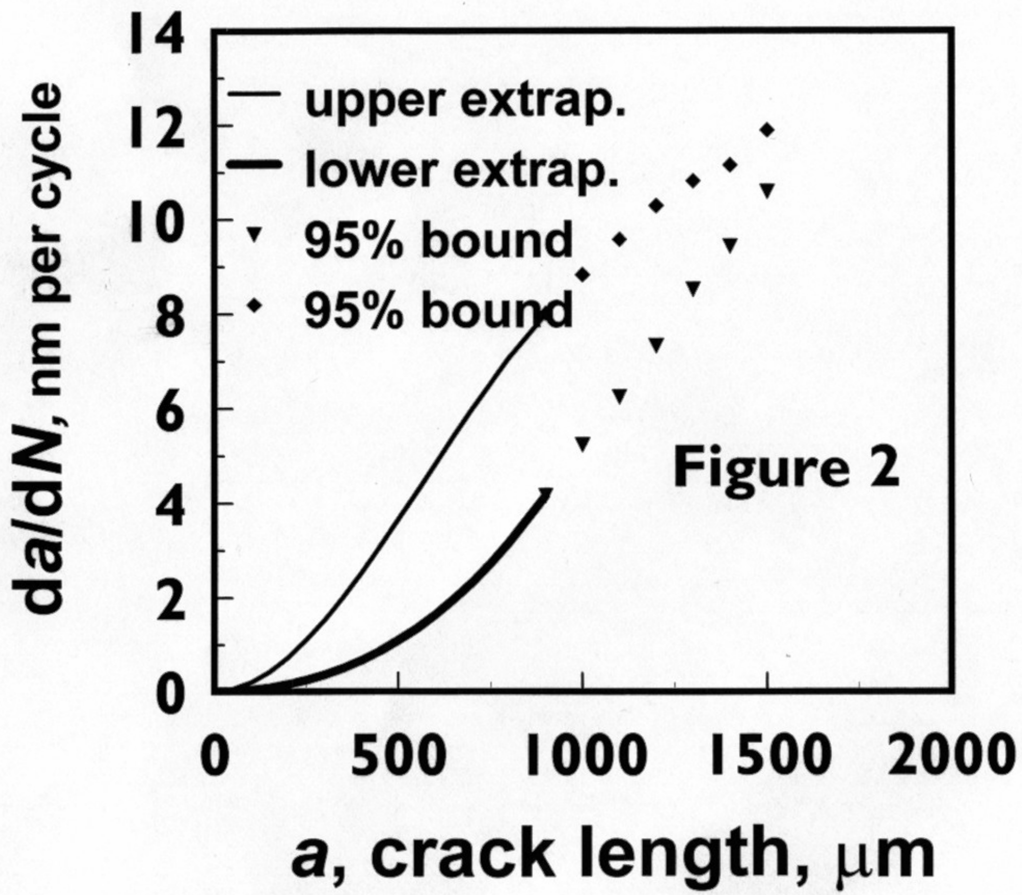
- Why log-log is not appropriate

- Possibility of extrapolation to zero a and da/dN with Cartesian



Interpolation

- Extensions of 95% curves back to initiation



Interpolation, Cont.

$$\frac{da}{dN} = pa^3 + qa^2 \qquad \int \frac{da}{f(a)} = \int dN + D$$

D found from initial values of a and N

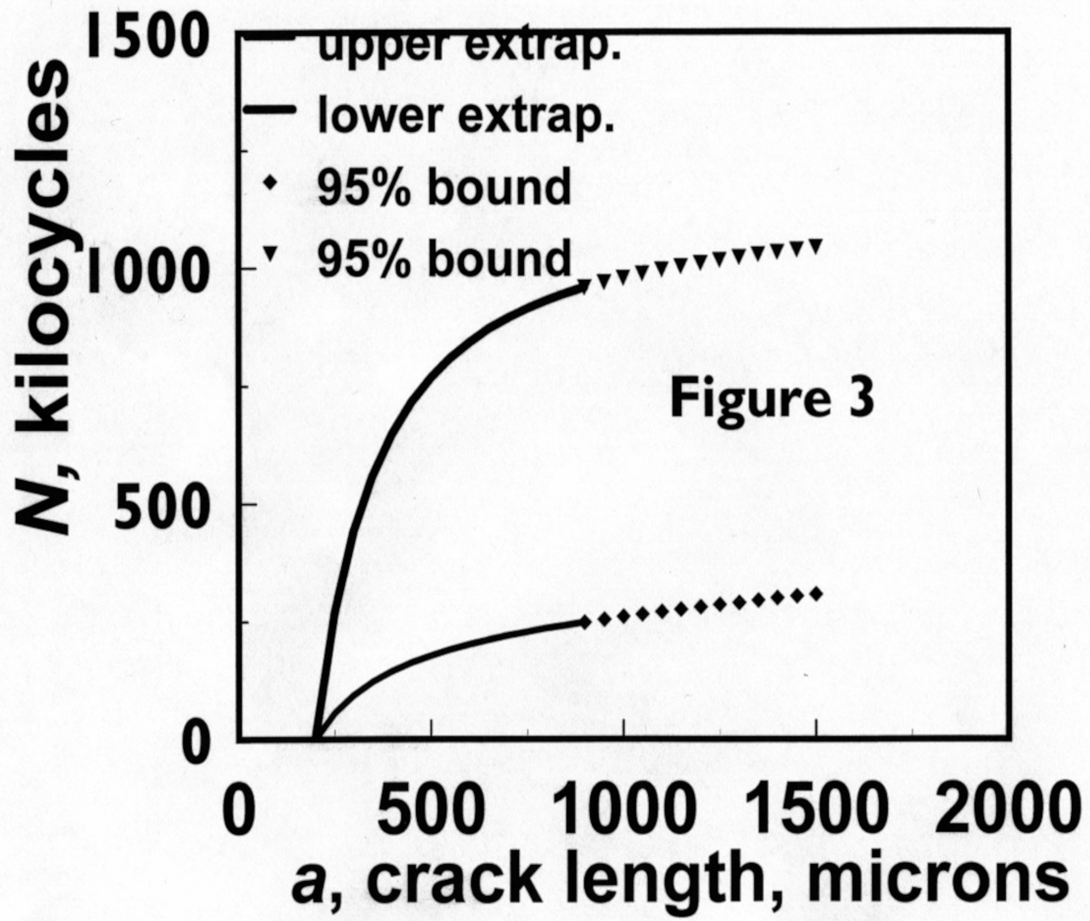
- our function

$$N = \frac{p}{q}\left[\log \frac{q + pa}{a}\right] - \frac{1}{qa} + D$$

- Crack must start growing from a finite initial value (because a → 0 only as N → -∞)

Interpolation, Cont.

- a = 200 μm for N = 0 (grain size)
- At 1,000 μm values of N are 250,000 and 1,000,000
- For design may add lower bound cycles – add to the cycles between 1,000 μm and critical long crack



Analysis of Standard Deviation

- ***Standard Deviations of Crack Growth Rates presented were calculated as follows:***

$$S^2 = \frac{1}{m-1}\sum_i \left(R_i - R_{mean}\right)^2$$

m = number of test specimens

R_i = ***growth rate*** = $(da/dN)_I$

R_{mean} = ***mean growth rate***

Trends in Standard Deviation

- *Behavior of S.D. can be represented by exponential function of the form:*

$$S = Ce^{D\Phi(a)}$$

- *a = crack length, C,D = Constants*
- *Nonlinear regression analysis provides the following:*

$$S = 0.81e^{\left[-2.299\cdot 10^{-6}(a-800)^2\right]}$$

Grain Intersection Analysis

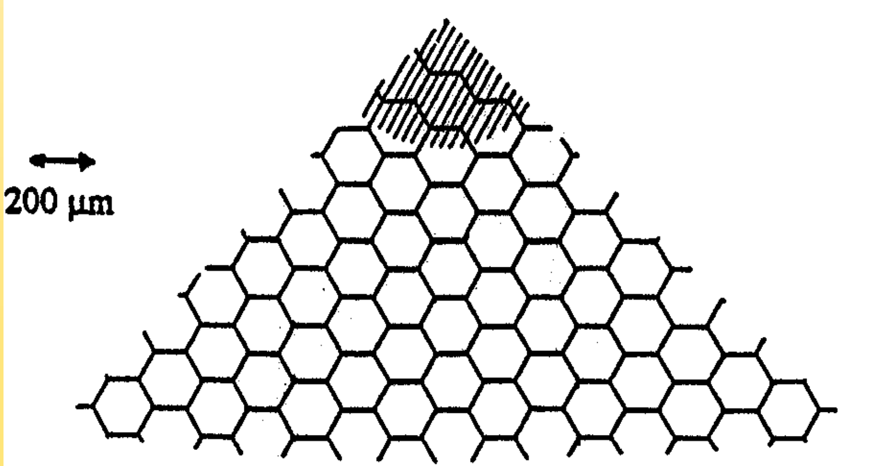
- ***Corner Crack fronts assumed to grow with quarter circular crack fronts.***

$$n = \frac{1}{2}\pi\left(\frac{a}{d}\right)$$

- ***n = number of grains intersected by crack front***

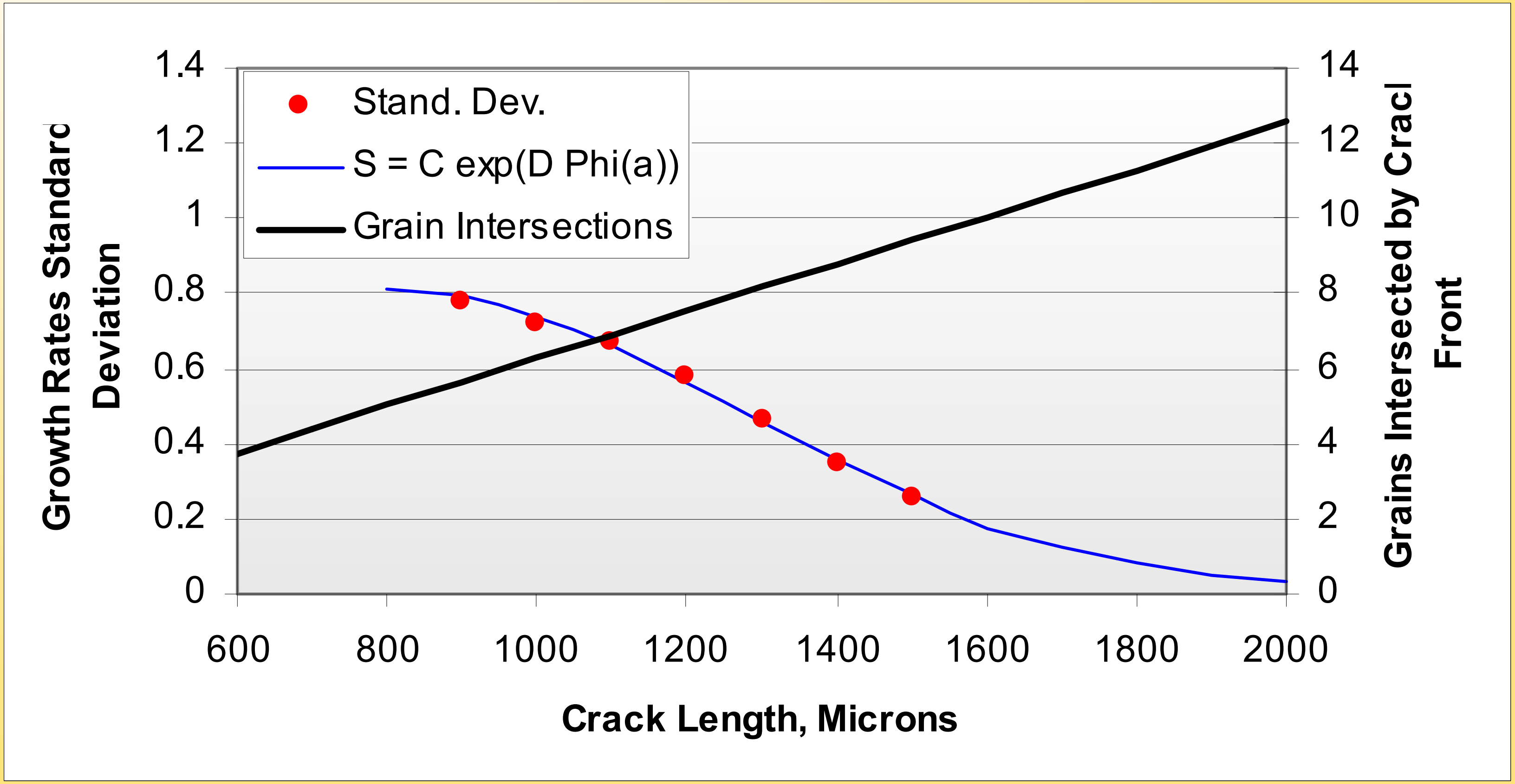
  a = Crack depth

  d = Mean grain diameter



S.D. and Grain Intersection Relations

- ***Grain Intersections and Standard Deviation Vs. Crack Length***



Grain Intersection Relations

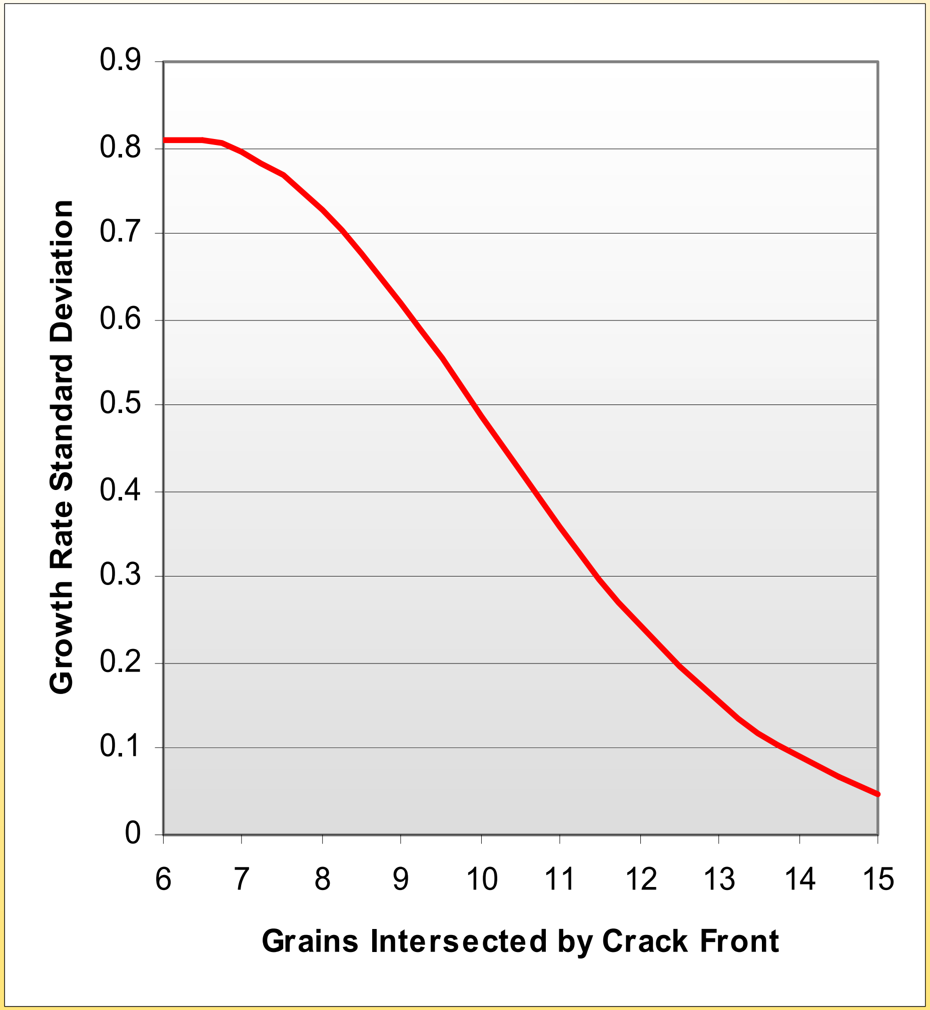
- ***Number of grains intersected by crack front is a linear function of the crack length.***
- ***S.D. can therefore be expressed as a function of number of intersections:***

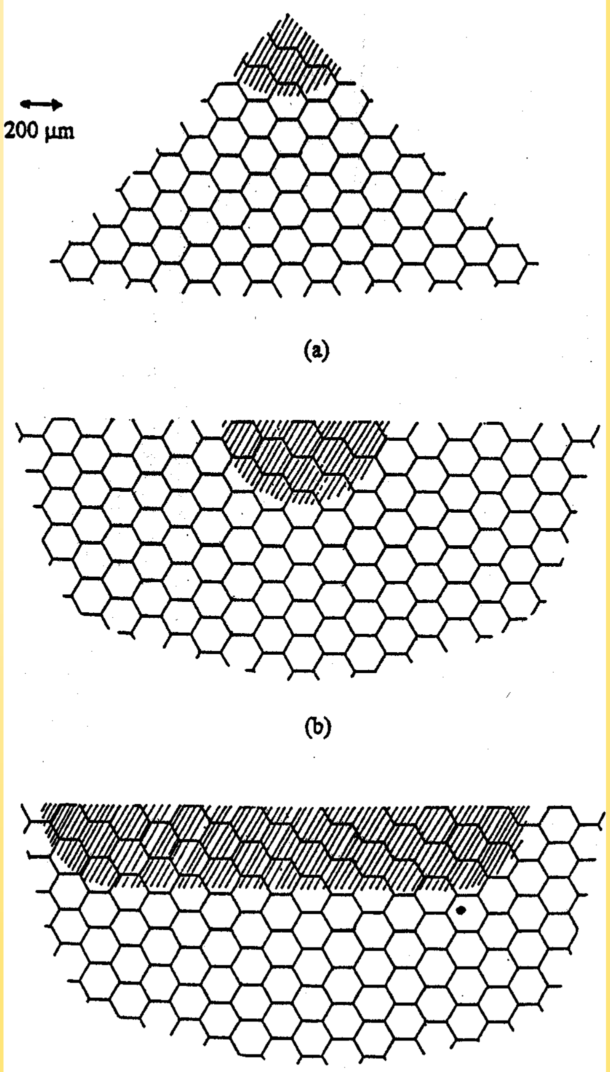
$$S = Ce^{D\Theta(n)}$$

- ***Applications to multiple crack shapes***
  - ***Ex. Thumbnail cracks intersect twice as many grains as similar depth corner cracks.***

Grain Intersection Relations

- *S.D. in Growth Rate vs. Grain Intersections*





Smooth Surface Multi-Site Cracking

- On smooth surfaces the onset of cracking can occur in randomly arranged clusters described as micro-multi-site cracking.

- Many cracks will arrest (“effectively non-propagating”)

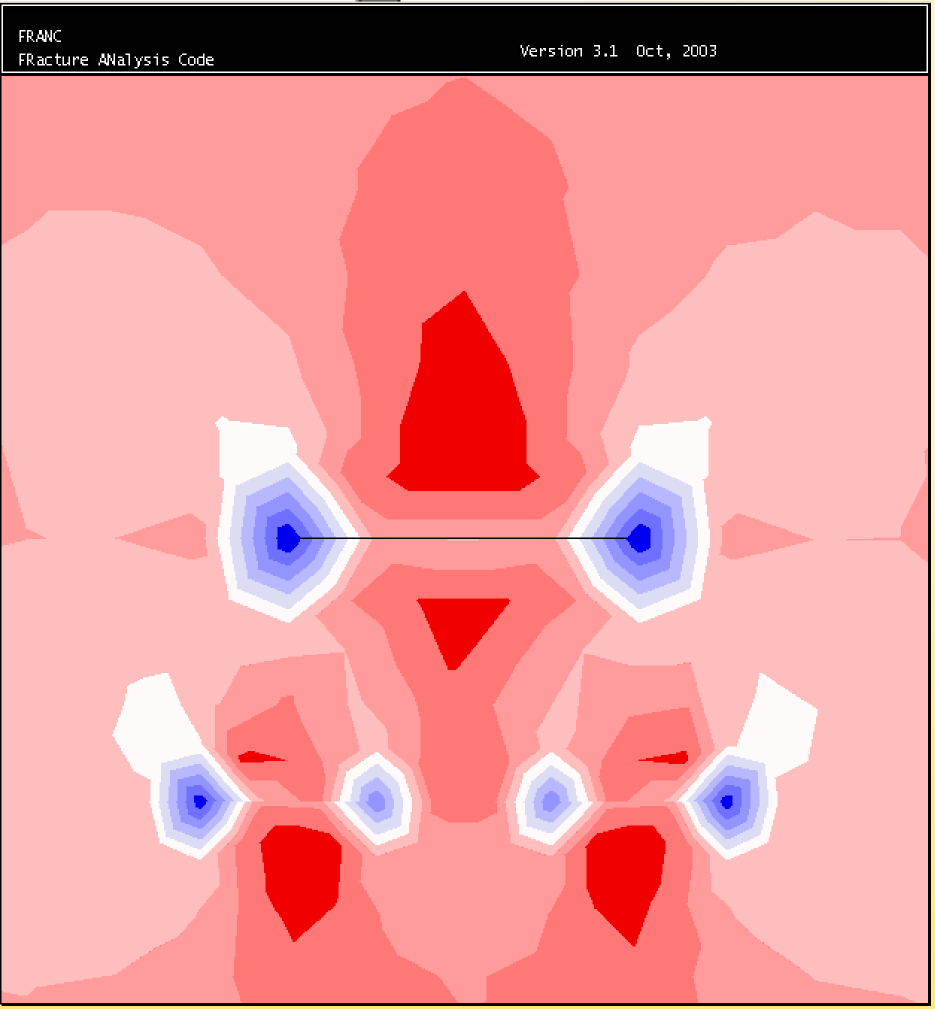
- Propagating (or dominant) cracks are those that continue to grow and lead to ultimate failure.

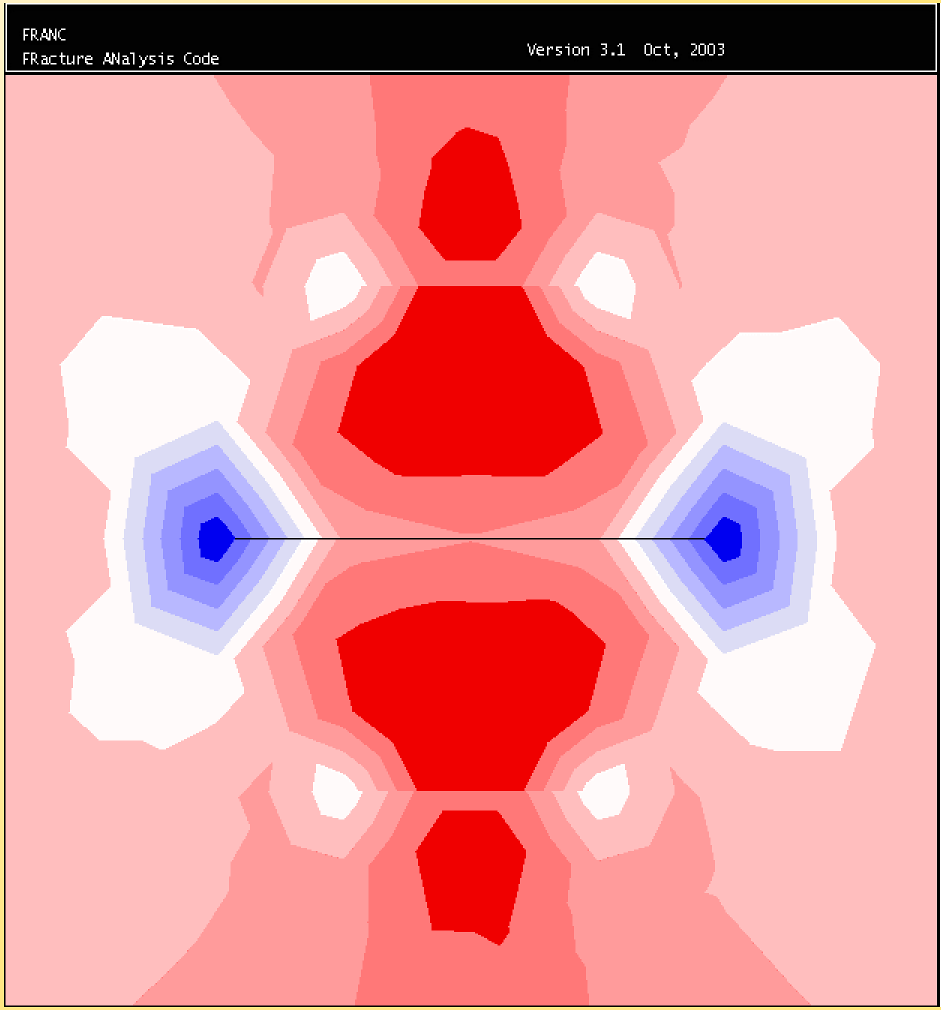
- Dominant cracks are influenced by the <u>shielding effects</u> of the network of nearby effectively non-propagating cracks.

Smooth Surface Multi-Site Cracking, Cont.

- ***Causes of Scatter***
  - Different material forms will have varying grain profiles: Ex. Grains in stock rod will be thin and elongated while those in plate are characterized by three dimensions; longitudinal, transverse and short transverse.
  - Small cracks fronts will thus encounter differing grain intersections and have differing scatter properties.
  - Randomly arranged crack cluster neighborhoods will affect scatter in addition to grain structure.

Illustrative Crack Shielding FEM





K_I=1.872, 1.455

K_I=1.913, 0.7129

**Performed on Franc 2d (Cornell University)*

Bi-Modal Crack Distributions

- ***Small Crack distributions are bi-modal***
  - **Both "dominant, propagating" and "effectively non-propagating" cracks have separate distributions.**
- ***Distributions cannot be separated in the early stages of loading.***
  - **Measurements are being made after dominant cracks can be identified (approx. 10 times the grain size).**
  - **Additional specimens are being run to same number of cycles to determine long crack size distribution.**
  - **Subsequent tests are being conducted at successively decreasing loading cycles.**

Current Experiments

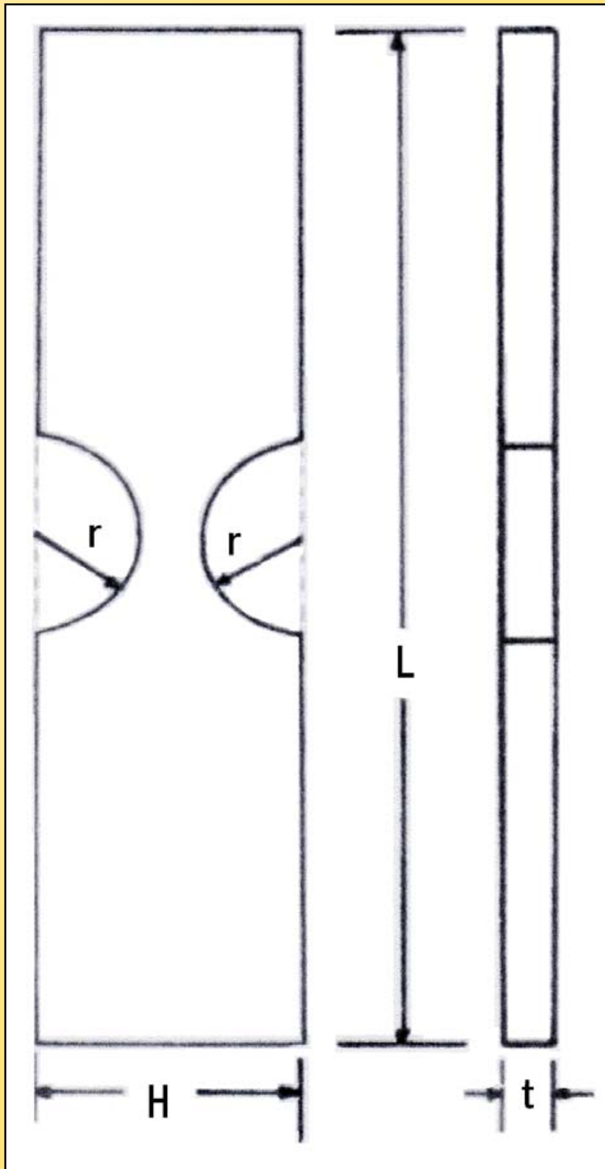
Aluminum 7075-T7351

- **Material Properties:**
  - *Mean* σ_{yield} *= 64.0 ksi*
  - *Mean* σ_{Ult} *= 75.3 ksi*

- **1/4 inch plate material with pancake grain structure.**
- **Mean linear intercept grain dimensions:**
  - *58.8 microns (Longitudinal)*
  - *76.1 microns (Transverse)*
  - *15.0 microns (Short Transverse)*

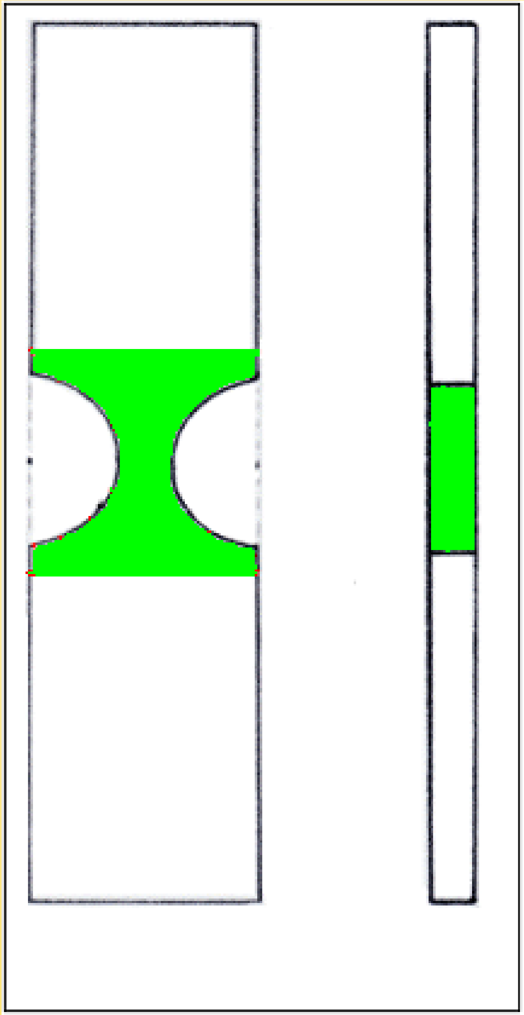
Current Experiments, Cont.

- *Material:* **Aluminum 7075-T7351**
- L = **8 in**, H = **2 in**
- t = **0.25 in**, r = **0.75 in**
- SCF = **1.2 (over ligament stress)**

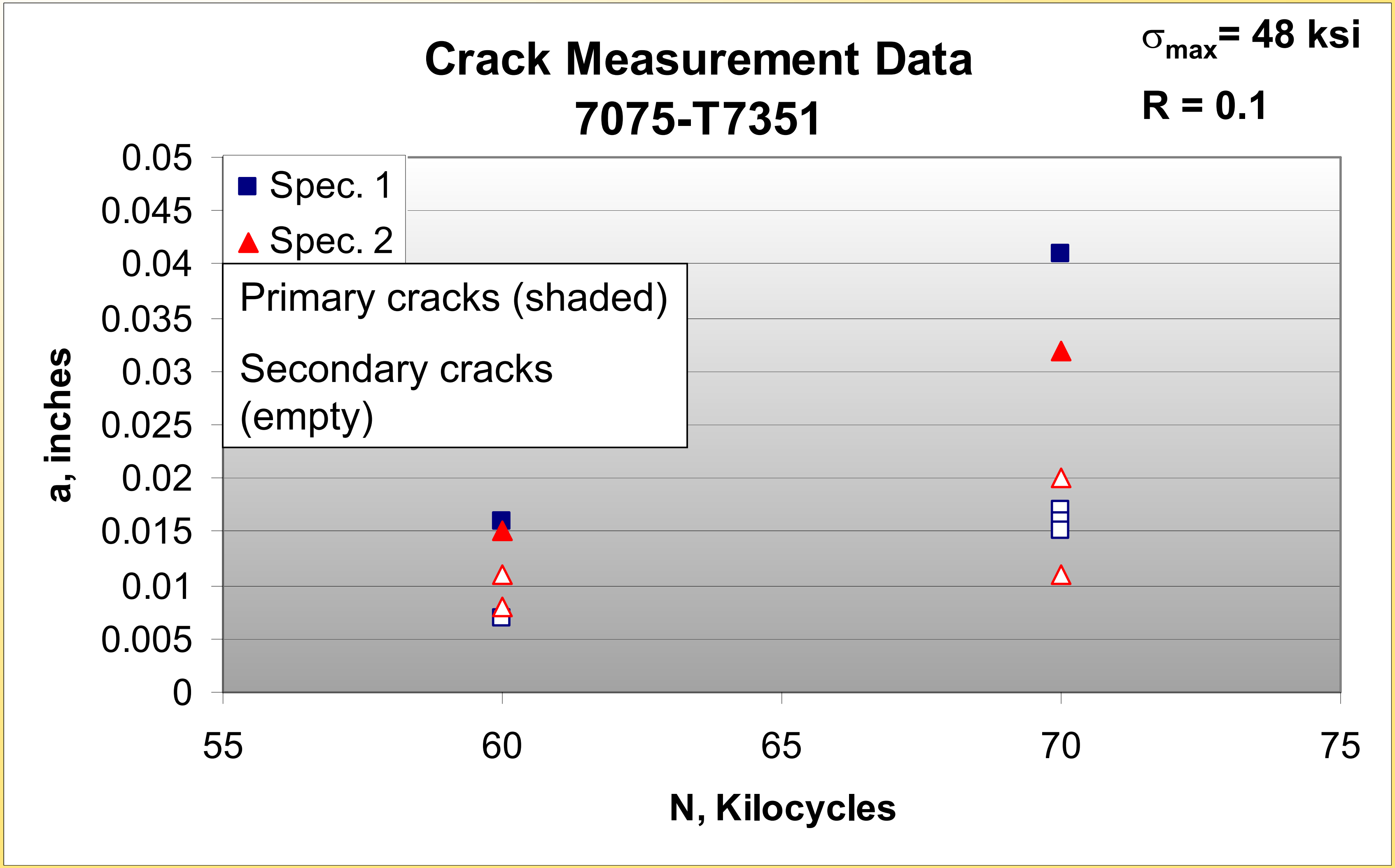


Current Experiments, Cont.

- **Test surface preparation includes entire mid-section of specimen.**
- **All corners are rounded.**
- **Three abrasive papers**
  - *240, 320, 600*
- **Three Diamond Pastes**
  - *15, 6, 1μ pastes applied with low nap cloth*



Crack Measurement Data



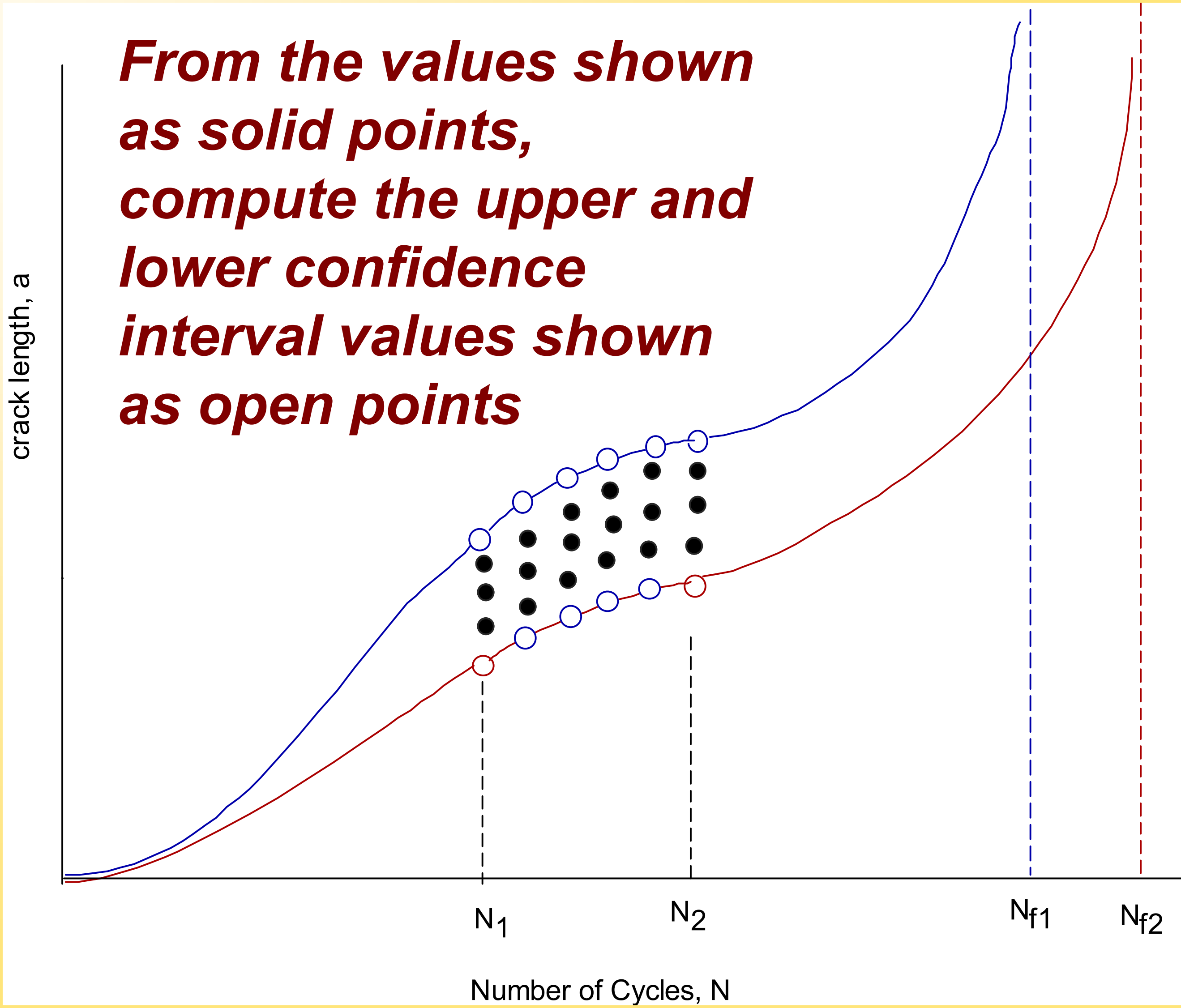
Analysis

- *The extrapolated growth rate versus crack length equations will be integrated to provide confidence intervals for crack length versus load cycles.*
- *This will give bounds on load cycles as a function of crack length.*
- *These results will then be used, in combination with long crack growth data, to estimate the possible range of lifetimes.*

Using crack length data obtained at N_1 and N_2 and a set of values from tests continued to fracture

Extrapolation/Analysis

- Confidence intervals computed for data at each cycle count using the Student-t distribution



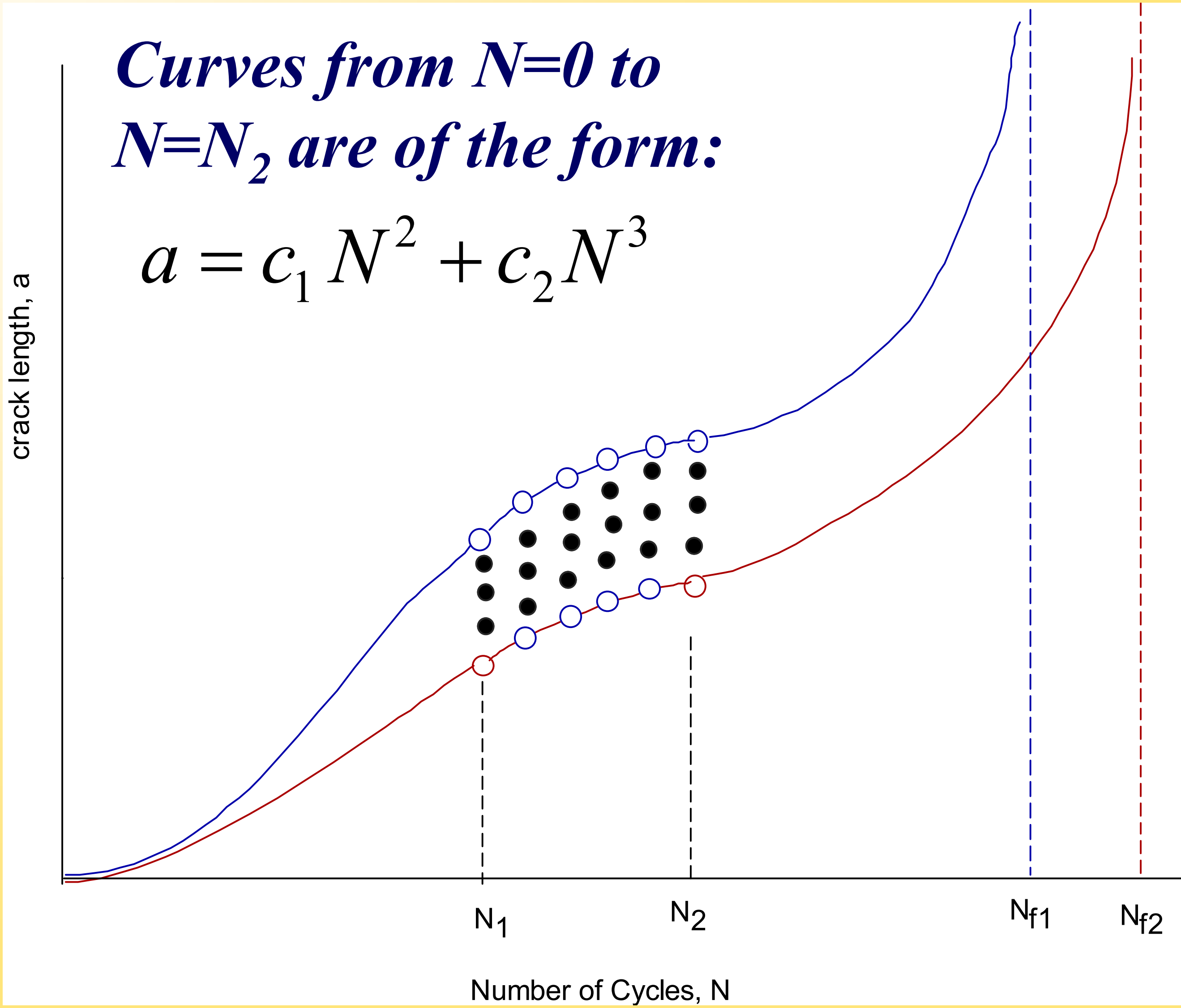
Extrapolation/Analysis

Curves from initiation to the N_2 point

- ***use (upper or lower) bound values of a at N_1 and N_2 to find c_1 and c_2***

Curves from N=0 to $N=N_2$ are of the form:

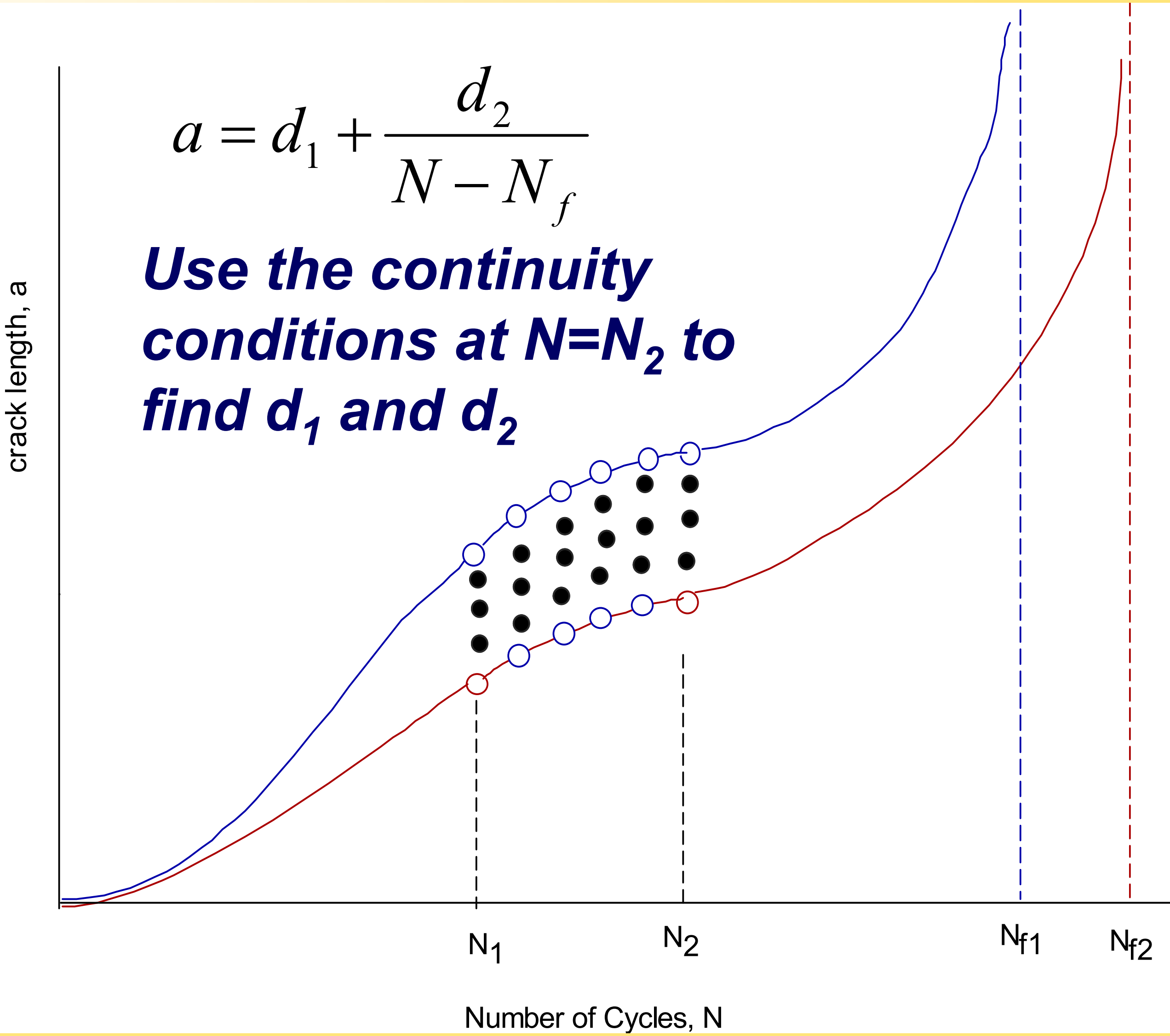
$$a = c_1 N^2 + c_2 N^3$$



Extrapolation/Analysis

Curves to failure confidence bounds

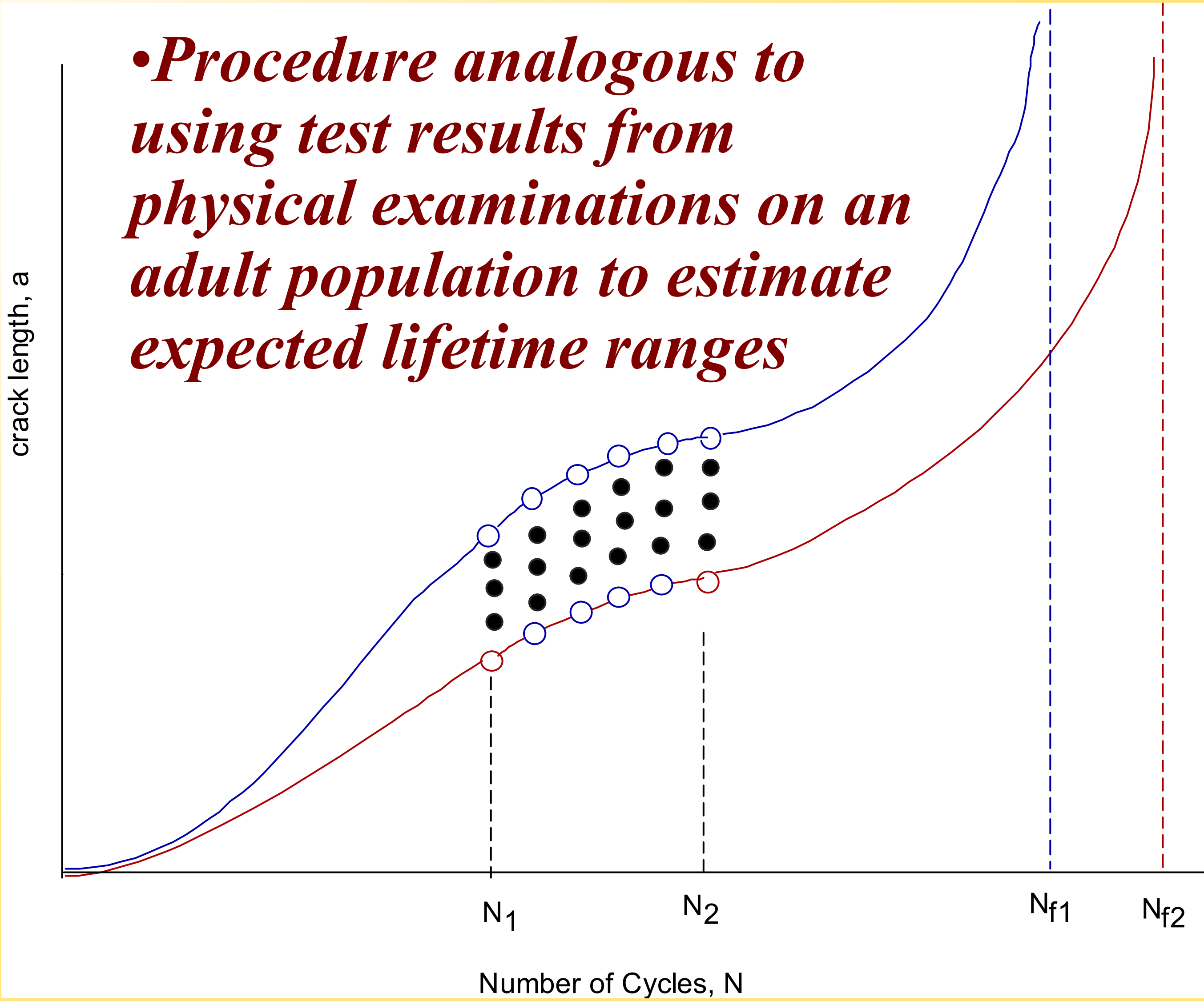
- ***For a continuation of the upper curve from N_2 to N_f, where N_f is a confidence limit for the smallest set of fracture values, use the equation shown***



Analysis for Lifetime

- **bounds on load cycles vs crack length (confidence intervals)**

- **combine w/ long crack growth data, to provide the possible range of lifetimes**

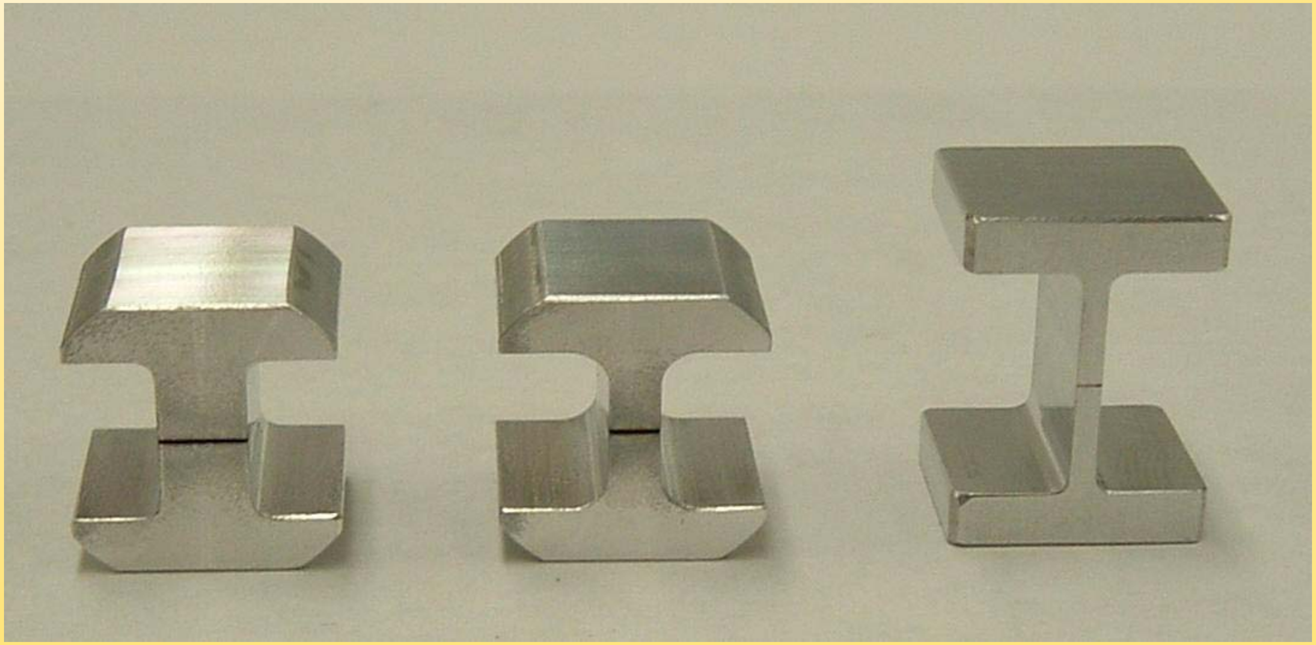


Objectives of Continuing Research

- ***Obtain dominant propagating crack distribution data for use in interpolating confidence bounds on load cycles versus crack length.***
- ***Possible use of effective S.I.F.'s to extend statistical results to include stress and crack geometry effects.***
- ***Determine effects of cluster crack arrangements on scatter.***

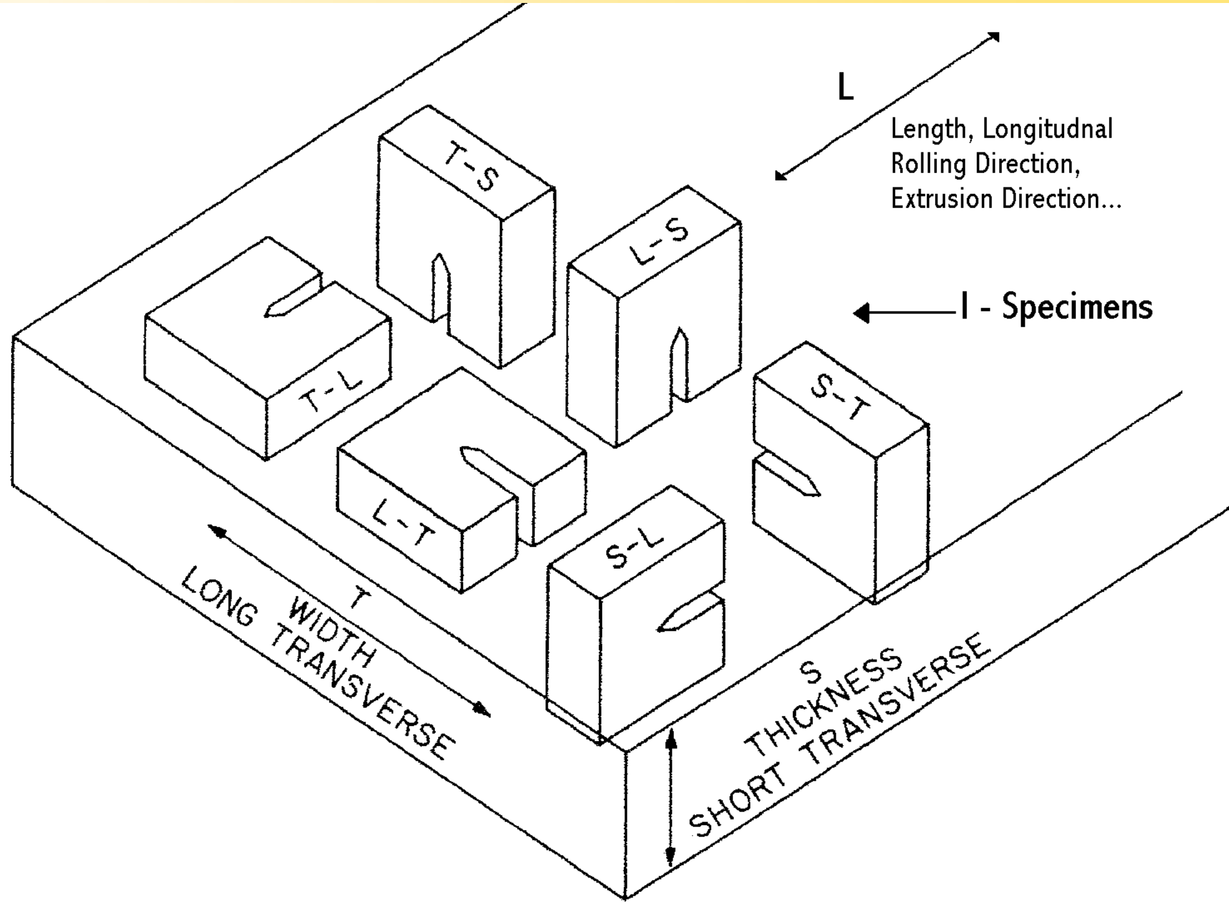
Additional Test Specimens

- *Miniature I specimen*
  - *Cracks grown at EDM notches.*
  - *Versatile and modifiable.*



Grain Orientation Study

- *Crack growth properties not constant with grain orientation.*
- *I – Specimen can be oriented to any grain orientation.*



Concluding Comment

- **Scatter in Fatigue Crack Growth originates within the Small Crack regime.**

- **The objective of our research is to use small crack growth data to develop confidence interval bounds that can be used as a basis for providing estimates for variations in lifetimes.**

- **Procedure analogous to using test results from physical examinations as a basis for estimating variations in expected lifetimes.**